INVESTIGATION OF THE HOMOGENIZATION EFFICIENCY OF THE SCREW AGITATOR, HELICAL RIBBON AGITATOR, GATE TYPE ANCHOR IMPELLER AND THE MULTI-PADDLE AGITATOR IN THE MIXING OF HIGH-VISCOSITY NEWTONIAN LIQUIDS

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Introduction

Upon the request of the Hungarian Chemical Industries Design Center the power consumption and the homogenization efficiency of screw and helical ribbon agitators, suitable for the mixing of high-viscosity liquids, have been compared with similar characteristics of conventional multi-paddle agitators and gate type anchor impellers. With this objective, it has been investigated which type of agitator permits to attain shorter homogenization time at identical power consumption, or in other words, which of the agitators will result in smaller homogenization work.

To establish this, on the one hand the power consumption of the agitators, and on the other hand, homogenization time had to be measured.

The geometrical data of the agitators investigated and of the equipment are contained in Table 1, while the drawings of the agitators are shown in Fig. 1.

Power consumption of the agitators

The power consumption of gate type anchor impellers has been determined in the laminar and the transition range, that of helical and combined helical ribbon screw agitators in the laminar range [1]. Relationship valid in the laminar range for the calculation of the power consumption of centric and eccentric screw agitators and screw agitators operated in a draught tube are found in Ref. [2].

The Eu-Re relationship of the multi-paddle agitator in the laminar and transition range, and that of the agitators mentioned above in the transition range have been determined in a tank of $D = 396$ mm diameter with basket curve bottom (Figs 2 and 3). Measuring equipment and procedure have been described in detail in our earlier communications [3, 4]. Molasses

Table 1

Geometrical ratios

Agitator	d mm	d/D		b/d
Multi-paddle*	148 277	0.70		0.116
Gate type anchor	375 360 193 335	0.95 0.91 0.85		0.07
Screw**	85 159 158	0.402 0.402 0.402		0.412 0.421 0.421
Helical ribbon	202 376	0.95		0.105
	191 356 337	0.90 0.85		0.108 0.104
Combined helical ribbon screw	d_r	$\frac{d_r}{D}$	$\frac{d_s}{d_r}$	$\frac{b_r}{d_r}$
	200 376	0.94	0.33	0.105

* On the mixing shaft, at identical distance from one another, 4 paddles of 60° inclination,
** Geometrical ratios of draught tube: $d_t/d = 1.09$; $l_t/d = 1.27$; $h_t/d = 0.41$

of different dilution have been used for the experiments, the viscosity of which varied between 10 and 180 Poise, and their density between 1.363 and 1.420 g/cm³.

Homogenization time

Homogenization time is that shortest time of operation of the agitator, during which the desired degree of homogeneity can be attained. Decrease in inhomogeneity (concentration or temperature equalization) can be readily followed by the determination of the local degree of homogeneity. Local degree of homogeneity at a given moment τ can be calculated with the following formula [5]:

$$X = \frac{1}{k} \sum_{1}^{k} \left| \frac{x(\tau) - x(0)}{x(\infty) - x(0)} \right| \cdot 100\% \tag{1}$$

where x is the variable measured (e.g. concentration or temperature).

of the agitators

l/d		l'/d	h/d	H/D	s/d		z
—		—	0.20	1.0	$\alpha = 60°$		4×2
0.92 0.94 0.94 0.97		—	0.025 0.05 0.05 0.075	1.0	—		—
1.50 1.50 1.54		— — —	0.16	1.0	1.0 1.0 0.50		1 1 1
1.0 1.0		0.17 0.17	0.025	1.16	1.0		2
1.06 1.06 1.10		0.18 0.18 0.19	0.05 0.075	1.16 1.16	1.0 1.0		2 2
$\frac{l_r}{d_r}$	$\frac{l_s}{d_s}$	$\frac{l'}{d_r}$	$\frac{h}{d_r}$	$\frac{H}{D}$	$\frac{s_r}{d_r}$	$\frac{s_s}{d_s}$	
1.00	2.25	0.17	0.05	1.16	0.5	1.5	1

$h_A = 0.31 \cdot d$

For the characterization of the whole process the change of X, the arithmetic mean of the degree of local homogeneity, is given as a function of time τ.

$$\overline{X} = \frac{1}{m} \sum_{1}^{m} X \,. \tag{2}$$

The mixing time needed to achieve a given average degree of homogeneity is called homogenization time τ_X.

In stable systems (e.g. pastes) the local degree of homogeneity according to Eq. (1) can be readily measured. As contrary to this, in the case of liquids it is difficult to determine the local degree of homogeneity. Therefore, researchers generally measure only at one, or at the most two, well selected points of the tank. Indeed, in the turbulent region this is sufficient, as several authors showed that for Re $> 10^3$ the degree of homogeneity is independent of the location [5, 6, 7]. In the transition and laminar ranges local degree of homogeneity depends already on location, but nevertheless, if there is no dead zone in the tank, the system can be satisfactorily characterized with local

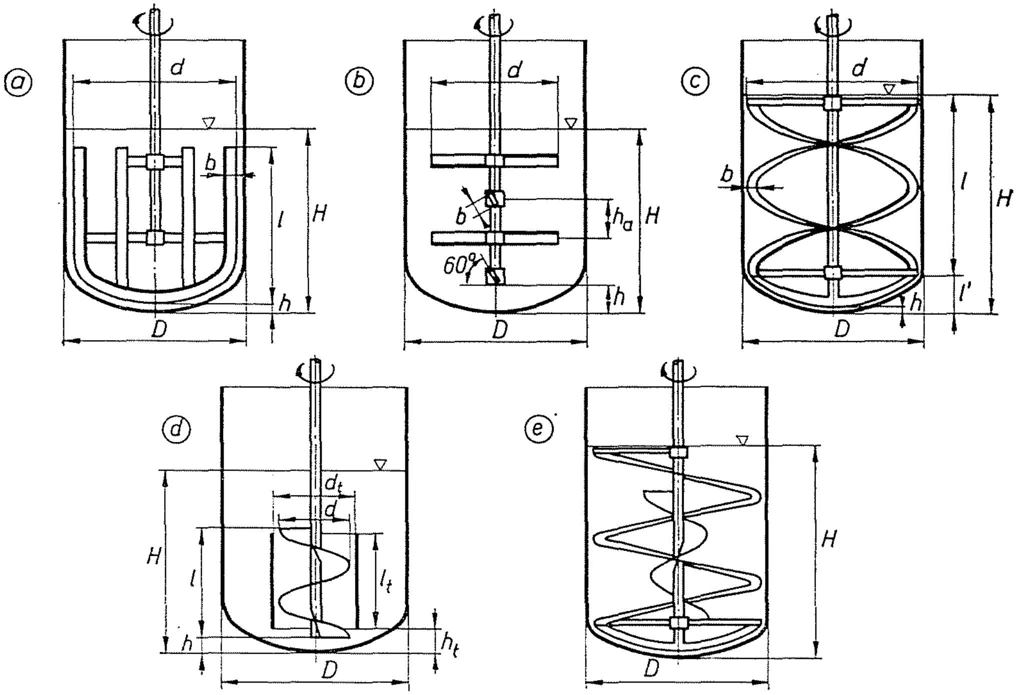

Fig. 1. Agitators used: a) gate type anchor impeller; b) multi-paddle; c) helical ribbon; d) screw in draught tube; e) combined helical ribbon screw agitators

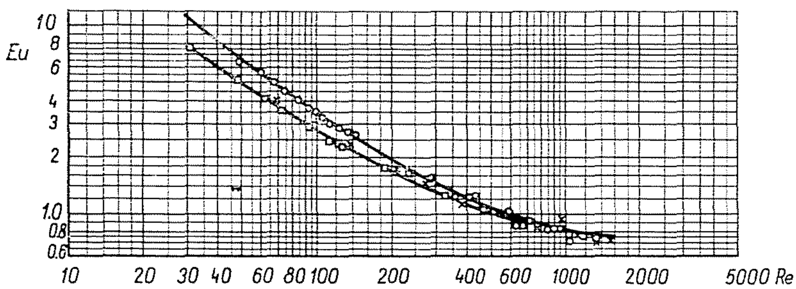

Fig. 2. Euler values measured with a helical ribbon agitator □ $d/D = 0.85$; × $d/D = 0.90$; ○ $d/D = 0.95$

degree of homogeneity measured at one or two points and with homogenization time belonging to it.

In the mixing of liquids, mainly the following three methods of testing are used for the measurement of homogenization time:

a) disturbance of concentration,
b) thermal method,
c) decolouration reaction.

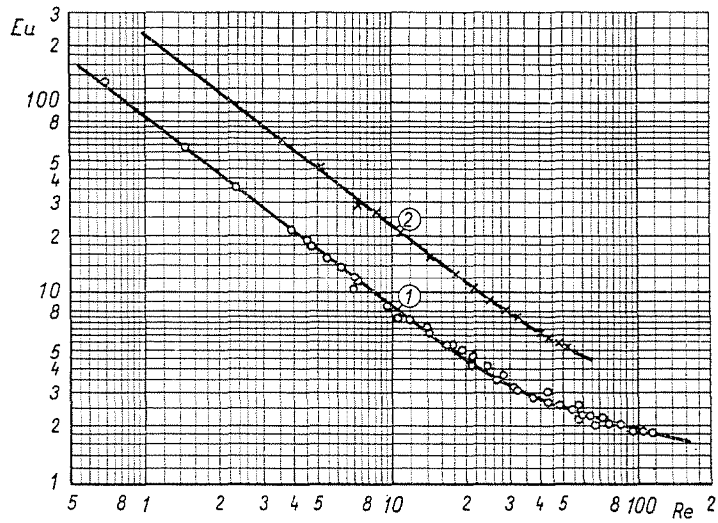

Fig. 3. Power consumption of a multi-paddle agitator (curve 1) and of a screw agitator ($s/d = 1.0$) operated in a draught tube (curve 2)

In all three methods a pulse-like disturbance is caused.

In the first method a disturbance of concentration is produced with concentrated salt solution, and the proceeding of homogenization is followed by the measuring of conductivity [5, 12—15], or by Schlieren technique [11]. In the thermal method heat is introduced into the liquid, and homogenization process is followed by temperature measurement [8, 9]. In the decolouration method colour change produced by redox or neutralization reaction is followed visually or with a photocell through the tank wall [5, 8, 10, 11, 16—21]. This process is very suitable for the detection of stable dead zones, appearing as residual coloured spots.

ZLOKARNIK [11] investigated the homogenization time of the anchor impeller and the finger agitator, and established that at identical speed of rotation the homogenization time of the finger agitator is considerably shorter than that of the anchor impeller.

The dependence of homogenization time on the pitch and the ribbon number of the helical ribbon agitator has been investigated by KÄPPEL [10] and NAGATA [20], and on the width of the ribbon by CARREAU [22]. The combined helical ribbon screw agitator has been studied by KÄPPEL [10], NAGATA [20], CHAVAN [23] and SINGLA [24].

The authors mentioned above did not investigate the effect of the change in agitator to tank diameter ratio on homogenization time and on homogenization efficiency.

Measurement of homogenization time

Homogenization experiments were carried out by two methods: the decolouration and the thermal method. The decolouration method was used for measurements with screw agitator, helical ribbon agitator and gate type anchor impeller in a glass tank of D = 212 mm diameter. The course of homogenization, i.e. of decolouration has been visually followed. With this method, the determination of the end point is rather subjective, but these measurements are excellently suited for the detection of dead zones forming in the mixed volume. Our experiments showed that no stable dead zone was formed in the case of any of the agitators investigated, thus it is sufficient to measure at two points in the thermal method.

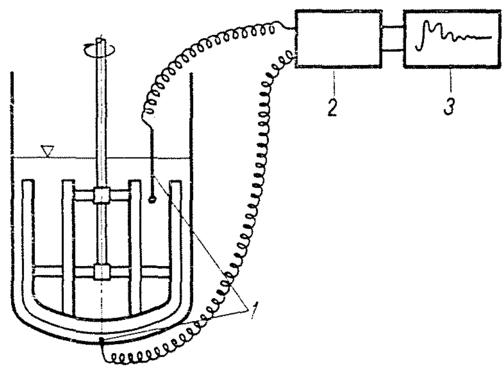

Fig. 4. Schematic diagram of the experimental equipment 1. thermistors; 2. Wheatstone bridge (Knauer Universal Temperatur-Messgerät); 3. line recorder compensograph

With the agitators listed in Table 1, homogenization experiments were carried out by the thermal method in a tank of diameter D = 396 mm.

The variable x is the temperature measured at two points of the tank with sensitive calibrated thermistors of small time constant. One of the thermistors was built into the center of the tank bottom, reaching into the liquid at a distance of 5 mm from the wall, while the other thermistor was located at 20 mm below the liquid surface, at 50—80 mm from the tank wall, depending on the type of the agitator. The thermistors were connected in opposite circuits in the Wheatstone-bridge of a measuring instrument (Type Knauer Universal Temperatur-Messgerät), and the temperature difference between the two points of the tank was measured and recorded as a function of time by a line chart compensograph. The bridge instrument was used at a sensitivity permitting the detection of a temperature difference as small as 0.001—0.002 °C. The scheme of the experimental equipment is shown in Fig. 4.

Disturbance by thermal pulse was applied to the system by filling under stirring 300—400 g of the same liquid as mixed in the tank, but of a temperature warmer by about 20 °C, introducing it at the midpoint of the liquid surface between the mixer shaft and the tank wall. The agitator and the temperature recorder were operated until the thermistors indicated no temperature difference any more.

This disturbance changes permanently the temperature of the mixed liquid. The change in temperature, Δt_z has been calculated from the heat balance.

In the thermal pulse disturbance method homogenization time was defined as follows:

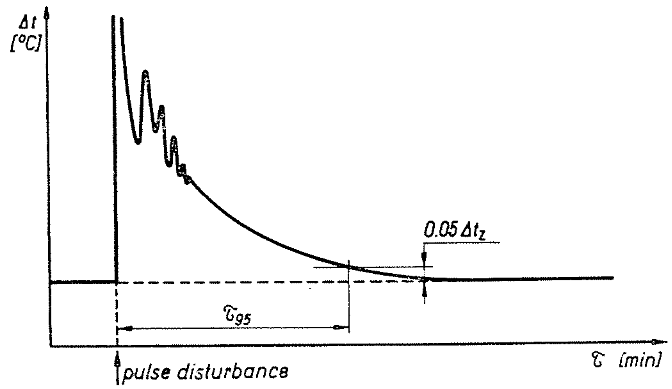

Fig. 5. Explanatocy figure for the determination of homogenization time

Homogenization time τ_X belonging to a degree of homogenization of $X\%$ is the time needed by the temperature difference between the two measuring points of the apparatus to be equal to 100 - X% of the change in temperature Δt_z, produced by the disturbance in the total liquid content.

From the temperature change curves measured, homogenization time τ_{95}, belonging to a degree of homogeneity of 95% has been determined as shown in Fig. 5. Measurements were carried out in the $Re = 1 \ldots .100$ range. Each measuring point represents the average of five measurements.

It should be mentioned that a part of our measurements has been repeated in a circuit where the thermistors were not connected in opposition, but the temperature curves were measured simultaneously but separately by the thermistors. Homogenization times calculated from these measurements were in agreement with values measured by thermistors connected in opposition.

The dimensionless homogenization number ($n \cdot \tau_{95}$) has been plotted as a function of the Reynolds number. In accordance with data in the literature [5, 9—14], it has been established that for $Re < 100$ the homogenization numbers of the helical ribbon and the combined helical ribbon screw agitators, further of the screw agitator operated in eccentric position or in a draught tube are constant. $n \cdot \tau_{95}$ values are listed in Table 2. The numerical value of the homogenization number, measured by the decolouration reaction, referred to the $n \cdot \tau_{95}$ value of the helical ribbon agitator of a diameter ratio of $d/D = 0.95$ is also indicated in the table. As will be noted, the reduced homogenization number of the agitators is near identical in both methods, but the numerical values of homogenization number measured are different. The value obtained by the decolourization method is about one third of the value obtained by the thermal method.

Table 2

Homogenization numbers measured in the laminar range

Agitator		$\frac{d}{D}$	$n\,\tau_{95}^{*}$ ±95% conf. int.	$n\,\tau_{95}^{**}$	$\frac{(n\,\tau_{95})^{*}}{(n\,\tau_{95})^{*}_{R95}}$	$\frac{(n\,\tau_{95})^{**}}{(n\,\tau_{95})^{**}_{R95}}$
Helical ribbon		0.95	255±17	75	1.00	1.00
		0.90	207±10	52	0.84	0.70
		0.85	250± 9	—	1.00	—
Combined helical ribbon screw		0.94	210±18	—	0.84	—
Screw $\frac{s}{d} = 1.00$	in draught tube $d_t/d = 1.09$	0.40	268± 8	81	1.07	1.08
	eccentric $e/D = 0.19$		161± 4	—	0.63	—
Screw $\frac{s}{d} = 0.50$	in draught tube $d_t/d = 1.09$	0.40	130±11	—	0.50	—
	eccentric $e/D = 0.19$		188±24	—	0.74	—

* By heat pulse disturbance method
** By decolouration method
R95 the helical ribbon agitator of diameter ratio $d/D = 0.95$

In the case of gate type anchor impellers and multi-paddle agitators, the homogenization number, shown in Figs 6—7, and in the reduced form in Fig. 8, depends on the Reynolds number. Figure 8 shows also reduced homogenization numbers calculated on the basis of the measurements by NOVÁK [14] with anchor impeller and helical ribbon agitator. The curves measured with gate type anchor impeller are in good agreement with data of NOVÁK measured with anchor impeller, particularly at higher Reynolds numbers. The multi-paddle agitator requires a very long time for homogenization, particularly at low Reynold numbers. There is no substantial difference between the homogenization times of the helical ribbon agitator and the

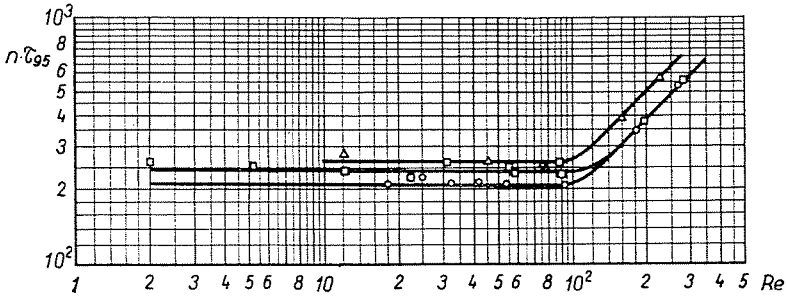

Fig. 6. Homogenization number of helical ribbon agitators △ $d/D = 0.85$; ○ $d/D = 0.90$; □ $d/D = 0.95$

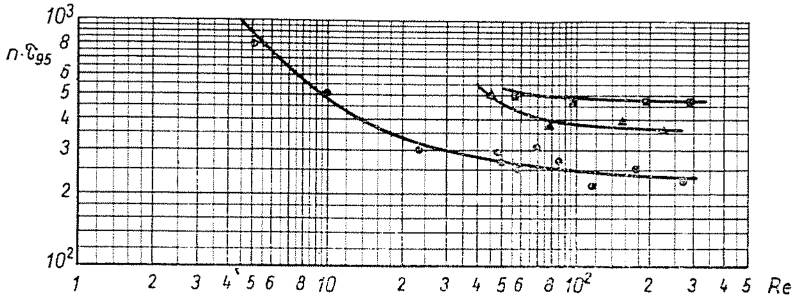

Fig. 7. Homogenization number of gate type anchor impellers ▲ $d/D = 0.85$; ● $d/D = 0.91$; ■ $d/D = 0.95$

combined helical ribbon screw agitator of identical diameter, the latter being less by about 15%. Similarly, there is no substantial difference between the homogenization numbers of helical ribbon agitators of different diameters. The homogenization number of the helical ribbon agitator of a diameter ratio $d/D = 0.90$ is by about 15% less than that of the agitators with diameter ratios $d/D = 0.95$ and 0.85.

The homogenization number of the gate type anchor impeller of diameter ratio $d/D = 0.91$ for an identical Reynolds number is e.g. by about 40% less than that of a diameter ratio $d/D = 0.85$, and half of the homogenization number of a gate type anchor impeller of a diameter ratio $d/D = 0.95$.

It should be noted that in tanks with concave bottom only helical ribbon agitators of a design shown in Fig. 1/c can be operated, the lower arc of which follows the curvature of the bottom of the tank. This lower arched part follows the shape of the anchor impeller. Without the arched part a zone of bad mixing is established below the agitator, and because of this, homogenization time increases to more than twofold.

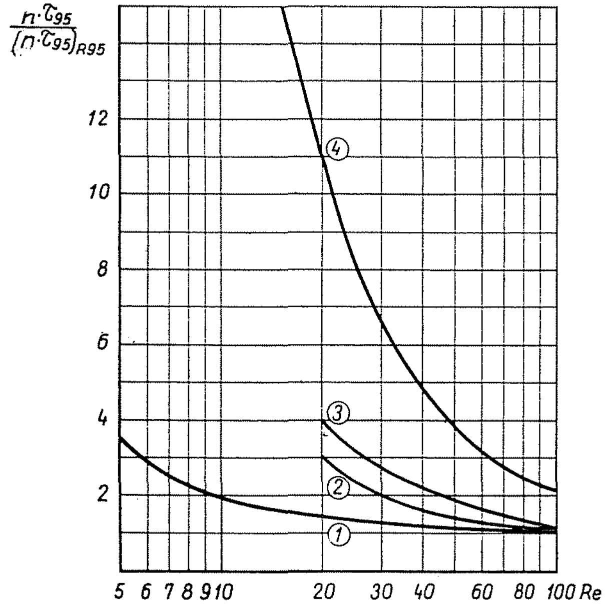

Fig. 8. Dependence of the reduced homogenization number 1. Gate type anchor impeller by thermal pulse method; 2. gate type anchor impeller by the colour reaction method; 3. anchor impeller by thermal pulse method [11]; 4. multi-paddle agitator by thermal pulse method; $(n \cdot \tau_{95})_{R95}$ is the homogenization number measured with the helical ribbon agitator of a diameter ratio $d/D = 0.95$

Homogenization efficiency of agitators

The classification of agitators according to homogenization efficiency was performed on the basis of homogenization time and power consumption. That agitator is the more efficient, which realizes the desired degree of homogeneity at a lower power consumption during the prescribed time. For the comparison of the agitators measuring data have been plotted in a diagram, the dimensionless groups on the axes of which contain besides the tank diameter and the physical characteristics of the liquid mixed only the homogenization time (abscisse), and the product of the power consumption and of the homogenization time i.e. the energy requirement of homogenization $(N \cdot \tau_{95})$.

Expressions plotted on the co-ordinate axes have been calculated from the following dimensionless quantities:

$$\frac{(N \cdot \tau_{95}) \cdot \varrho}{D \cdot \mu^2} = Eu \cdot Re^2 \cdot (n \cdot \tau_{95}) \cdot \left(\frac{d}{D}\right) \tag{3}$$

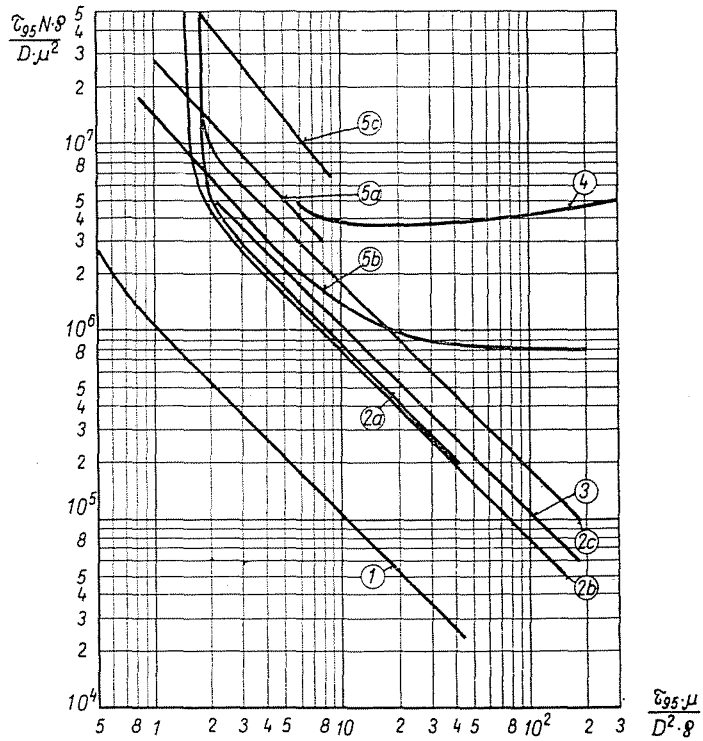

Fig. 9. Comparison of the homogenization efficiency of agitators
1. screw agitator in draught tube ($dt/d = 1.09$; $s/d = 1.0$); 2. helical ribbon agitator a) $d/D = 0.85$; b) $d/D = 0.90$; c) $d/D = 0.95$; 3. combined helical ribbon screw agitator; 4. multi-paddle agitator; 5. gate type impeller a) $d/D = 0.85$; b) $d/D = 0.91$; c) $d/D = 0.91$

and

$$\tau_{95} \cdot \mu / D^2 \cdot \varrho = (n \cdot \tau_{95}) Re^{-1} \left(\frac{d}{D} \right)^2 . \tag{4}$$

Thus, measuring data have been analysed in the following functional relationship:

$$\frac{(N \cdot \tau_{95}) \cdot \varrho}{D \mu^2} = f \left(\frac{\tau_{95} \cdot \mu}{D^2 \cdot \varrho} \right) . \tag{5}$$

That agitator will be the more efficient, the curve of which, giving the functional relationship (5), is located lower.

The efficiency of the agitators is compared in Fig. 9. Straight lines are seen to be obtained for the helical ribbon, combined helical ribbon screw and screw agitators, as the following relationships are valid in the laminar range:

$$Eu \cdot Re = A \tag{6}$$

$$n \cdot \tau_{95} = \text{constant.} \tag{7}$$

From Eqs 3...7, the equation of the straight lines is:

$$\frac{(N \cdot \tau_{95}) \cdot \varrho}{D \cdot \mu^2} = K_L \left(\frac{\tau_{95} \cdot \mu}{D^2 \cdot \varrho} \right)^{-1} \tag{8}$$

where

$$K_L = A(n\tau_{95})^2 \left(\frac{d}{D} \right)^3 \tag{9}$$

K_L defined by Eq. (9) is identical with the group $N \cdot \tau^2/D^3\mu$, introduced by Hoogendorn [8]. On the basis of Eq. (8) that agitator is the more efficient, the K_L value of which is lower.

The K_L values of helical ribbon, combined helical ribbon screw and screw agitators are contained in Table 3.

The following can be established on the basis of Fig. 9 and Table 3:

Table 3

Homogenization efficiency of the agitators in the laminar range

Agitator		$\frac{d}{D}$	$\frac{s}{d}$	$n \cdot \tau_{95}$	Eu · Re	$K_L \pm 95\%$ conf. int.
Helical ribbon		0.95	1.00	255	330	$1.8 \cdot 10^7 \pm 0.2 \cdot 10^7$
		0.90		207	247	$7.8 \cdot 10^6 \pm 0.7 \cdot 10^6$
		0.85		250	205*	$8.5 \cdot 10^6 \pm 0.6 \cdot 10^6$
Combined helical ribbon screw		0.94	1.0	210	277	$1.0 \cdot 10^7 \pm 0.2 \cdot 10^7$
Screw	in draught tube $d_t/d = 1.09$	0.40	1.00	268	230	$1.0 \cdot 10^6 \pm 0.07 \cdot 10^6$
	eccentric $e/D = 0.19$			161	131**	$2.3 \cdot 10^5 \pm 0.1 \cdot 10^5$
Screw	in draught tube $d_t/d = 1.09$	0.40	0.50	130	307	$3.3 \cdot 10^5 \pm 0.6 \cdot 10^5$
	eccentric $e/D = 0.19$			188	203**	$4.8 \cdot 10^5 \pm 1.1 \cdot 10^5$

* Calculated from Eu values read off from Fig. 2 at Re = 30.
** Value calculated by equation in Ref. [2].

— Of all agitator types investigated the screw agitator operated in eccentric position is the most efficient. In eccentric position the energy requirement of a screw agitator of square pitch is half of that of a screw agitator of pitch $s/d = 0.5$.

— Of the screw agitators operated in a draught tube ($d_t/d = 1.09$), the screw agitator with half-pitch is the more efficient, its power requirement being about one third of the screw with square pitch.

— Of the helical ribbon and combined helical ribbon screw agitators of identical diameter ratios the latter is the more efficient. (For identical homogenization times its power requirements is by about 30% lower.)

— For helical ribbon agitators the diameter ratio $d/D \simeq 0.90$ is optimal, the power requirement of homogenization being in this case the lowest.

— In the case of $\tau \cdot \mu/D^2 \cdot \varrho > 20$, the use of gate type anchor impeller for homogenization tasks is not recommended, but even at $2 < \tau \cdot \mu/D^2 \cdot \varrho < < 20$ its power requirement ($N \cdot \tau_{95}$) is by about 50% higher than that of a helical ribbon agitator of identical diameter. In the case of gate type anchor impellers too, $d/D \simeq 0.90$ is the optimal diameter ratio.

— The multi-paddle agitator requires in the case of $\tau\mu/D^2\varrho > 10$ considerably more energy than the other agitators.

— It is not recommended to use a helical ribbon agitator for homogenization, if $\tau \cdot \mu/D^2\varrho < 2$.

Summary

The authors mixed Newtonian liquids of high viscosity with helical ribbon, screw, combined helical ribbon screw agitators, gate type anchor impeller and multi-paddle agitator. The power consumption of the agitators and homogenization time have been measured. It has been established that the screw agitator of square pitch, operated in eccentric position is the most efficient. Optimal diameter ratio of helical ribbon agitators and gate type anchor impellers is $d/D \simeq 0.90$. The gate type anchor impeller requires in the case of $\frac{\tau\mu}{D^2\varrho} > 20$, and the multi-paddle agitator in the case of $\frac{\tau\mu}{D^2\varrho} > 10$ considerably more energy than the other agitators.

Symbols

b	width of mixing element, [m]
D	diameter of tank, [m]
d	diameter of agitator, [m]
d_t	internal diameter of draught tube, [m]
e	eccentricity, offset of the centre of the impeller from the centre of the vessel, [m]
H	height of liquid level in the tank, [m]
h	distance of the agitator from the bottom of the tank, [m]
h_a	distance of the mixing elements of the multi-paddle agitator, [m]
h_t	distance of the draught tube from the bottom of the tank, [m]
K_L	constant of Eq. (8), —
k	number of repeated measurements in Eq. (1), —
l	height of the agitator, [m]
l'	height of the lower mixing element mounted on the helical ribbon and combined helical ribbon screw agitators, [m]
l_t	length of the draught tube, [m]
m	number of measuring (sampling) points in the homogenization experiment, —
N	power consumption of the agitator, [W]
n	speed of rotation of the agitator, [l/s]
s	pitch of helical ribbon, combined helical ribbon screw and screw agitators, [m]
x	variable in Eq. (2)
X	local degree of homogeneity, —
$\overline{X}$	average degree of homogeneity, —
z	ribbon number of helical ribbon and combined helical ribbon screw agitators, —
Δt_z	change in liquid temperature due to heat pulse disturbance, [°C]

$Eu = \frac{N}{d^5 n^3 \cdot \varrho}$ Euler number of mixing, —
$n \cdot \tau_X$ homogenization number belonging to degree of homogeneity X, —
$Re = \frac{d^2 \cdot n \cdot \varrho}{\mu}$ Reynolds number of mixing, —
ϱ liquid density, [kg/m³]
μ viscosity of liquid, [kg /m · s]
τ_X homogenization time belonging to the degree of homogeneity X, [s]

Subscripts:
$-_s$ screw agitator
$-_r$ helical ribbon agitator
$-_t$ draught tube
$-_X$ degree of homogeneity
$-_{R95}$ helical ribbon agitator of diameter ratio d/D = 0,95
$-_L$ laminar range

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